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Simulating the fate of water in field soil–crop environment

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Abstract

This paper presents an evaluation of the Root Zone Water Quality Model(RZWQM) for assessing the fate of water in the soil–crop environment at the field scale under the particular conditions of a Mediterranean region. The RZWQM model is a one-dimensional dual porosity model that allows flow in macropores. It integrates the physical, biological and chemical processes occurring in the root zone, allowing the simulation of a wide spectrum of agricultural management practices. This study involved the evaluation of the soil, hydrologic and crop development sub-models within the RZWQM for two distinct agricultural systems, one consisting of a grain corn planted in a silty loam soil, irrigated by level basins and the other a forage corn planted in a sandy soil, irrigated by sprinklers. Evaluation was performed at two distinct levels. At the first level the model capability to fit the measured data was analyzed (calibration). At the second level the model's capability to extrapolate and predict the system behavior for conditions different than those used when fitting the model was assessed (validation). In a subsequent paper the same type of evaluation is presented for the nitrogen transformation and transport model.

At the first level a change in the crop evapotranspiration (ETc) formulation was introduced, based upon the definition of the effective leaf area, resulting in a 51% decrease in the root mean square error of the ETc simulations. As a result the simulation of the root water uptake was greatly improved. A new bottom boundary condition was implemented to account for the presence of a shallow water table. This improved the simulation of the water table depths and consequently the soil water evolution within the root zone. The soil hydraulic parameters and the crop variety specific parameters were calibrated in order to minimize the simulation errors of soil water and crop development.

At the second level crop yield was predicted with an error of 1.1 and 2.8% for grain and forage corn, respectively. Soil water was predicted with an efficiency ranging from 50 to 95% for the silty loam soil and between 56 and 72% for the sandy soil.

The purposed calibration procedure allowed the model to predict crop development, yield and the water balance terms, with accuracy that is acceptable in practical applications for complex and spatially variable field conditions. An iterative method was required to account for the strong interaction between the different model components, based upon detailed experimental data on soils and crops.

Keywords: RZWQM; Model calibration; Model validation; Soil hydraulic properties; Crop evapotranspiration; Crop growth

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1. Introduction

The development of regulations for safeguarding the water resources from N leaching from agricultural fields can be made easier by the availability of comprehensive simulation models to estimate N movement. Many models are available today to simulate the fate of water and N in the soil–crop environment. We must ensure that models and their parameters are evaluated with as much rigor as possible. In order to collect appropriate data for evaluation, the experiments need to be properly designed. A poor sampling arrangement could lead to the rejection of a good model or the acceptance of a poor one (Addiscot et al., 1995). Some parameters often cannot be measured directly or easily and the second best option is to obtain such parameters by fitting to data, independent of the type of the problem to be simulated (Addiscot et al., 1995).

The Root Zone Water Quality Model (RZWQM) is an agricultural system model developed over the last 12 years by USDA-ARS, Great Plain Systems Research Unit in Fort Collins, Colorado, USA, in cooperation with several other scientists. It integrates the state-of-the-science knowledge of agricultural systems into a tool for agricultural research and management, environmental assessment, and technology transfer. More recently the environmental aspects of RZWQM have been highlighted. In this context, the primary use of RZWQM is as a tool for assessing the environmental impact of alternative management strategies on a field-by-field basis and predicting management effects on crop production. At the current state of knowledge of field complexities, the model is better for comparative purposes as opposed to rigorous quantitative predictions.

The reliability of RZWQM depends on how well each individual process is represented in the model and on the accuracy of the measured parameters needed to run the model. The model components have undergone extensive verification, evaluation and refinement in collaboration with several users in the USA. These components are water movement (Ahuja et al., 1993, 1995), pesticide transport (Ahuja et al., 1993, 1996), evapotranspiration (Farahani et al., 1996; Farahani and Ahuja, 1996), subsurface tile drainage (Johnsen et al., 1995; Singh et al., 1996), organic matter/nitrogen cycling (Ma et al., 1998), and plant growth (Nokes et al., 1996; Ma et al., 2000). However, there are significant interactions among different components of the system. To achieve acceptable simulation results for nitrate transport, a good description of crop growth, N uptake and soil water fluxes is required. Also, to properly simulate the water balance, a good description of crop development and root growth is needed, since they determine evapotranspiration and water uptake. So it is not possible to evaluate the nitrogen component without evaluating the crop and hydrology component of the model.

When the RZWQM model was applied to the Mediterranean conditions (Cameira et al., 1998), some problems were found, with respect to the existence of a fluctuating shallow water table, the uncertainty caused by macropore flow and lateral groundwater flows, the crop evapotranspiration (ETc) formulation used in the model, and the transformations within the nitrogen cycle for specific conditions of temperature and humidity. The objectives of this study were to carefully evaluate the model under these conditions, using a systematic, iterative, procedure for calibration, and modify some model components if necessary. For the water balance, two alterations were introduced in the model. The first one comprised a new option to define boundary condition to solve the Richards equation (variable upward and downward fluxes) in order to account for lateral groundwater fluxes. The second alteration was a change in calculating the stomatal resistance of the canopy. The calibrations involved estimation of the unknown and unmeasurable parameters for some of the conditions or adjusting the measured values due to unknown components, such as macropores and lateral flow, variety specific crop parameters, and changes in soil properties due to water table and flooding.

Due to extensive information the work is presented in two papers. This first paper contains the hydrologic (soil water and evapotranspiration) and crop growth components, and the second paper will deal with nitrogen transformation and transport results, using bulk mineralisation experimental data.

2. RZWQM overview

As a system model, RZWQM includes several components or modules aiming to describe a complete agricultural system. Each subsystem is illustrated in detail in several publications, e.g. Ahuja et al. (1999a). In this paper we will focus on the components of interest for the present study.

2.1. The hydrologic component

This module includes a sub-module of macropore flow and transport, along with sub-modules of infiltration and redistribution in the soil matrix, related physical processes and management effects (Ahuja et al., 1999b). The matrix soil hydraulic properties are described in the model by the functional forms suggested by Brooks and Corey with slight modifications (Ahuja et al., 1999b). The Green-Ampt equation is used to calculate infiltration rates into an homogeneous or a layered soil profile.

The top soil horizons are assumed to have cylindrical macropore channels and the bottom horizons to have planar cracks. Continuous macropores are idealized to be vertical and well dispersed within the soil matrix continuum. The continuity extends to a water table or any other depth. However, a certain number of dead-end macropores are assumed to branch horizontally from the continuous pores in each soil horizon. The maximum flow-rate capacity of the macropores, K_{mac} ($m\,s^{-1}$) is calculated using the Poiseuille's law assuming gravity flow (unit hydraulic head gradient).

Between successive rainfall or irrigation events, the soil water is redistributed by a mass conservative, finite-difference numerical solution of the Richards' equation (Celia et al., 1990)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h,z)\frac{\partial h}{\partial z} - K(h,z)\right] - S(z,t) \tag{1}$$

where θ is the volumetric water content ($cm^3\,cm^{-3}$), t is time (h), z is the soil depth (cm), h is the pressure head (L), K is the unsaturated hydraulic conductivity ($cm\,h^{-1}$), expressed as function of h and z, and S is the root water uptake ($cm\,h^{-1}$) given by Nimah and Hanks (1973)

$$-S(z,t) = \frac{[H_{rs} + (R_{res.z}) - h(z,t) - h_o(z,t)]R_a(z)K(h)}{x_r\Delta z} \tag{2}$$

where H_{rs} is the water pressure head in the roots at the crown level (L); R_{res} is the root resistance (TL^{-1}) assumed constant and equal to 1.05 and $R_{res.z}$ the term introducing the gravity and head losses in H_{rs}; $h(z,t)$ is the average soil water pressure head at the depth z; h_o is the osmotic pressure head (L); x_r is the distance between the roots and the point where $h(z,t)$ was considered, assumed to be equal to unity (L); Δz is soil depth increment (L) and; $R_a(z)$ is the proportion of active roots in the depth increment Δz obtained from the crop growth model.

The sum of $S(z,t)$ over the entire root zone cannot exceed the potential transpiration demand. The equation is solved iteratively by varying H_{rs} until the demand is met, using the condition that H_{rs} does not fall below h_{min} (-1500 kPa—wilting point). After H_{rs} reaches h_{min} this value is assumed to hold steady, whereas the sum of total S over all depths falls below the potential demand.

The initial condition to solve Eq. (1) is given as:

$$h = h(z); \quad t = 0, \quad z \geq 0 \tag{3}$$

The surface boundary condition is an evaporative flux until the surface pressure head falls below a minimum value ($-20{,}000$ cm) at which time a constant head condition is used

$$-K\frac{\partial h}{\partial z} + K = c_n E_{vp}; \quad z = 0, 0 < t < t_e, \qquad h(z=0) > h_{min} \tag{4}$$

$$h = h_{min}; \quad z = 0, \quad t > t_e \tag{5}$$

where E_{vp} is the potential evaporation rate on the soil surface, after accounting for the effect of residue cover ($cm\,h^{-1}$) and the fraction of soil surface not shaded by the canopy (c_n); h_{min} is the minimum value of soil water pressure head (cm) set equal to $-20{,}000$ cm, and t_e is the time up to which the E_{vp} can be sustained by soil (h).

The bottom boundary condition can be specified as a unit gradient, a constant or a variable flux, or a constant pressure head

$$\frac{\partial h}{\partial z} = 0; \quad z = z_r, \quad t > 0 \tag{6}$$

or

$$-K\frac{\partial h}{\partial z} + K = D; \quad z = z_r, \quad t > 0 \tag{7}$$

or

$$h = h(z_r); \quad z = z_r, \quad t > 0 \tag{8}$$

where D is the drainage rate out of the root zone (LT^{-1}) or upward flux into the root zone, and z_r is the bottom of the root zone (cm). The D accounts for any lateral flow from groundwater to soil or vice-versa. In the numerical solution, this flux is applied to nodes below groundwater table above z_r. This flux had to be calibrated in order to maintain water balance in the unsaturated zone above the water table.

2.2. Evapotranspiration component

The evapotranspiration (ET) calculation in RZWQM is based on the Shuttleworth and Wallace (1985) dual surface version of the Penman–Monteith (Monteith, 1965) equation, extended to include evaporation from residue-covered soils with the form

$$\lambda ET = CC(PM_c) + CS(PM_s) + CR(PM_r) \tag{9}$$

where λET is the total flux of latent heat above the canopy (J); CC, CS and CR are coefficients based upon the fractions of area covered by the canopy, bare soil and residue, respectively, and the correspondent aerodynamic and surface resistances; and PMc, PMs and PMr are the Penman–Monteith equations applied to the canopy, bare soil and residues, respectively.

In the absence of a surface residue, CR is zero and Eq. (9) reduces to the original Shuttleworth and Wallace model. In the absence of a crop, CC is zero and Eq. (9) becomes a Penman–Monteith type soil evaporation model. On the other hand, as the canopy cover approaches unity, CS and CR approach zero and Eq. (9) becomes the original Penman–Monteith model. Detailed formulation of the terms CC, CS and CR can be found in Farahani and DeCoursey (1999). Solving the extended *S–W* model for crop transpiration and soil and residue evaporation, requires estimates of the surface and boundary layer resistances.

In the RZWQM, aerodynamic resistances (r_a^s—aerodynamic resistance between the ground surface and the mean canopy height and r_a^a—aerodynamic resistance between the mean canopy and measurement height) are calculated following the formulation presented by Shuttleworth and Gurney (1990). The objective of the model is to obtain a potential rate, with the actual rate being obtained through a soil water transport model.

The mean canopy boundary layer resistance, r_a^c, is calculated as

$$r_a^c = r_b/(2LAI) \tag{10}$$

where $r_b/2$ is the mean leaf boundary layer resistance of amphistomatous leaves per unit surface area of vegetation and LAI is the leaf area index. The formulation chosen for the bulk stomatal resistance of the canopy, r_s^c, is

$$r_s^c = r_{st}/(2LAI), \quad \text{for LAI} \leq 2 \tag{11}$$

$$r_s^c = r_{st}/LAI, \quad \text{for LAI} > 2$$

where $r_{st}/2$ is the mean stomatal resistance of amphistomatous leaves, assuming values between 150 and 350 s/m, typical of well watered crops.

Therefore, this formulation allows the bulk stomatal resistance of the canopy to decrease without restrictions, accompanying the increase in LAI.

2.3. Plant production component

The plant production model is a generic plant model, which can be parameterized to simulate a specific crop. The basic equations can be found in Hanson (1999). Rates of the simulated processes are modified by environmental fitness functions, which are a measure of the suitability of the environment for providing for the needs of the plant. The crop phenological development model uses a modified Leslie (1945) probability approach. Plant growth processes are represented by photosynthesis, respiration, carbon allocation and tissue mortality. Roots grow in areas that are most fit as determined by soil layer temperature, moisture, aeration and calcium and aluminum concentrations. The algorithms used for predicting root growth and distribution under soil stress were modified from the CERES-MAIZE model (Jones and Kiniry, 1986).

3. Materials and methods

3.1. Model calibration and validation procedure

Models like RZWQM require a detailed set of parameters. Some of these parameters cannot be easily measured or determined. Also, conditions of the natural soil–plant-atmosphere system are difficult to define for some parameters requiring a calibration for the site, crop, and variety. The user is confronted with the task of determining which parameters to calibrate and how to do it.

Kumar et al. (1999) related the discrepancies between measured and RZWQM simulated water and nitrates contents to the lack of calibration of the plant growth component. This is because in RZWQM, water and nutrient balance are a function of the crop growth and development. Therefore, an iterative calibration approach, involving the soil, plant development, crop evapotranspiration and nutrient sub models, is needed to account for the interactions among soil water, available nitrogen and crop production. This approach will reduce the error propagation between model components. This paper presents the detailed description of the hydrological and crop development module calibrations. The description of the nutrient module calibration is being presented with detail in a subsequent paper, which also includes the transport of nitrates in the root zone. However, as an iterative methodology was used, the results presented in this paper related with crop development, yield and water balance were obtained after the calibration of all the modules, including the nutrients.

The model was calibrated for the silty loam and the sandy soil using experimental data from 1996 and 1997, respectively. Two years' data were used for calibration because experiments were conducted on two different soils with two different crop varieties. The different model components were considered calibrated when the root mean square error of the simulations (RMSE) were lower than the mean standard deviation (MSD) of the measured data. RMSE and MSD were calculated as

$$\mathrm{RMSE} = \left(\sum_{k=1}^{n}(S_k - O_k)^2/n\right)^{0.5} \tag{12}$$

$$\mathrm{MSD} = \frac{\sum_{k=1}^{n}\mathrm{SD}_k}{n} \tag{13}$$

where S_k are the simulated values, O_k are the observed values, n is the number of measurements and SD is the standard deviation of measured values.

The starting moisture profile and the depth of the water table gave the initial conditions for solving Eq. (1). At the soil surface, precipitation and potential evapotranspiration were given as top boundary flux conditions. At the bottom a variable flux was imposed in the silty loam profile creating the flexibility to either use an upward or downward flow. For the sandy profile a unit gradient was used as bottom boundary condition.

The flow chart describing the calibration process is presented in Fig. 1. First, an independent calibration of the soil hydraulic properties was performed using water content data from infiltration and redistribution in a bare soil. A two step method was used: (i) K_s and θ_s were calibrated using infiltration profiles; and (ii) $K(h)$ and $\theta(h)$ were calibrated using redistribution profiles measured from field experiments. The RZWQM was run in inverse mode to obtain these properties.

For the calibration of θ_s and K_s for the silty loam soil the RZWQM model was used in two modes: (i) considering the soil as one domain corresponding to the homogeneous matrix; and (ii) considering two domains which include the flow through the soil matrix and through the macropore channels. For the one domain approach the Brooks and Corey parameters were calibrated. For the two domain approach, the macropore volume, M_{ac} ($\mathrm{cm^3\,cm^{-3}}$) at each soil layer and their average radius; and the dead end macropores by soil layer as a percentage of total macroporosity (M_d) were also calibrated. For the sandy soil only the one domain approach was used since there was no evidence of macropore flow.

When the RMSE's of the soil water simulations were lower than the MSD's of the measured data, the hydraulic parameters were considered calibrated and were used in the calibration of parameters associated with the water use by the crop (ETc) and the root extraction pattern. However, these two latter variables are also dependent upon the crop development. So, the calibration of the following model components was performed simultaneously.

In the crop development model two types of parameters were calibrated. They were the duration of each growth stage and the crop-specific parameters (Table 1). The latter reflect the effect of the environment over crop development for each production system. The first four values shown in Table 1

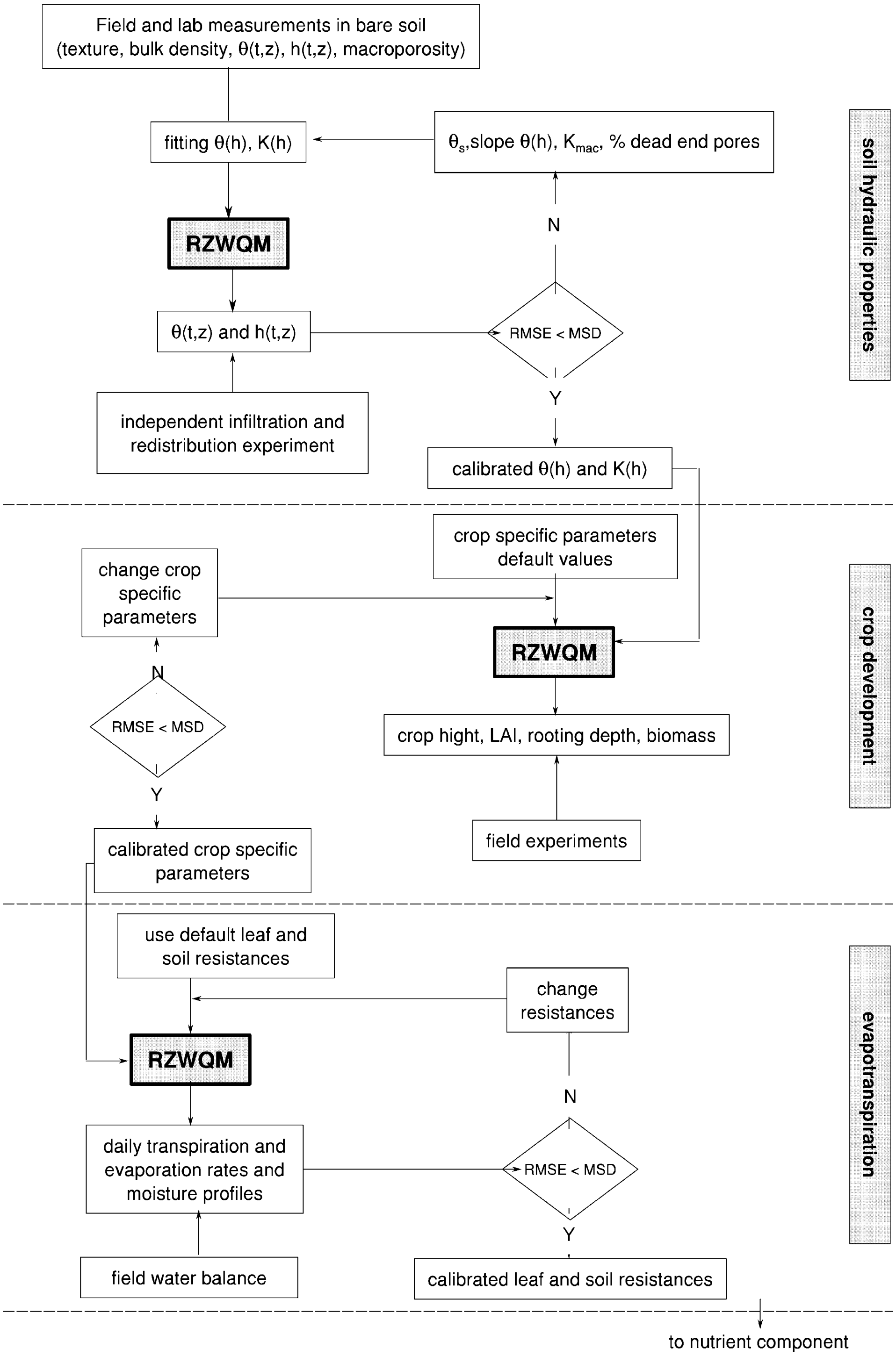

Fig. 1. Flow chart describing the iterative calibration methodology used for the RZWQM.

Table 1
Phenological and site-specific parameters after calibration of the crop development component

Parameter	Default	Grain corn	Forage corn
(1) Minimum time for the beginning of the germinating phase (days)	5	5	5
(2) Minimum time for the beginning of emergence (days)	15	15	15
(3) Minimum time for the beginning of the four leaf stage (days)	20	30	25
(4) Minimum time for the beginning of the reproductive stage (days)	30	40	30
(5) Maximum N uptake rate (g/plant/day)	5	2.5	1.0
(6) Relation N uptake/biomass (0–1/day)	0.12	0.05	0.05
(7) Specific leaf density (g/LAI)	11.5	13.5	13.5
(8) Photosynthetic efficiency in the flowering phase (0–1)	0.45	0.95	0.85
(9) Photosynthetic efficiency in the seed formation phase (0–1)	0.6	0.90	0.80

are used to adjust the duration of each crop stage. The following values are the crop-specific parameters. Increasing parameter (6) results in a decrease in biomass. Decreasing parameter (7) results in an increase in biomass. Parameters (6) and (7) can be adjusted to change the slope of the biomass curves. Parameter (8) increases yield while above ground biomass is kept constant. Parameter (9) does the same but later in the growing season. Parameters (8) and (9) can be changed to adjust the harvest index which is the ratio between yield and total above ground biomass. For this particular component the model developers suggest that the simulations must be within 15% of the measured control variables, which are above ground biomass, yield and leaf area index (Hanson, 1999).

The calibration process was initiated using the default value of 5 for parameter (1). After the simulation the estimated biomass was compared with the measured. If the error was higher than 15% parameter (6) was adjusted. Then parameter (7) was adjusted in order to reduce the error to approximately 10%. When necessary, the harvest index was adjusted by changing (8) and (9). The process was iterated as necessary (Fig. 1).

The calibration of the water balance components in a cropped soil involves the evapotranspiration and the soil hydraulic parameters previously calibrated for bare soil conditions. The control variables for this process are soil water, water fluxes through the bottom boundary and crop evapotranspiration.

The calibration of the evapotranspiration model was performed using calculated daily and cumulative values of crop evapotranspiration. The parameters available for calibration are the stomatal resistance, r_{st}, and the soil resistance r_s^s to evaporation.

After the calibration of each model component the simulations of the previous components were checked and, if necessary, calibration was refined.

Model validation must be performed for distinct climatic and management conditions so the model can be tested for extreme conditions. For this reason, the experimental work must be less intense than for the calibration process. Thus, for this study the flux variables (like the upward flux from the water table and the crop evapotranspiration) were not measured or calculated from field data. Only state variables (crop development and soil water) were measured and used as control variables for the predictions. The model was validated using independent data collected during the 1998 crop seasons under the current management practices.

Residual analysis of the predictions was based upon modeling efficiency (EF) calculated as (Loague and Green, 1991; Legates and McCabe, 1999)

$$\mathrm{EF} = \left(\sum_{k=1}^{n} (O_k - \bar{O})^2 - \sum_{k=1}^{n} (P_k - O_k)^2 \right) / \sum_{k=1}^{n} (O_k - \bar{O})^2 \tag{14}$$

where P_k are the predicted values, O_k are the observed values, n is the number of samples and $\bar{O}$ is the mean of the observed data.

Legates and McCabe (1999) recommend the use of the maximum absolute error (ME) and the root mean square error (RMSE) to quantify the errors in terms of the magnitude of the variable

$$\mathrm{ME} = \max|P_k - O_k|_{k=1}^{n} \tag{15}$$

Optimal values for RMSE, EF and ME are 0, 1 and 0, respectively. Loague and Green (1991) suggested the use of graphical displays in order to find trends, types of errors and distribution patterns.

3.2. Experimental fields

The experiments were performed during the years of 1996, 1997 and 1998 in two plots in an experimental station at Coruche, in the Sorraia Watershed in the South of Portugal. The climate is Mediterranean with an average annual rainfall (1950–1980) of 706 mm. Most of the rain occurs between October and May. Summers are hot and dry.

The soil in one of the plots is a deep silty loam Eutric Fluvisol (FAO classification), often flooded during winter, with poor internal drainage, a shallow water table and having a water retention capacity of 236 mm/m. The soil in the other plot was a sandy Eutric Cambisol (FAO classification) with good drainage but low water retention capacity (103 mm/m). Table 2 presents some measured physical characteristics of both soils.

Grain corn (FAO 600) and forage corn (FAO 200) have been grown in the silty loam and sandy soils, respectively, for many years under current Sorraia Watershed management practices as described in Cameira et al. (2003a).

3.3. Measurements

In each plot, three replicate sub-plots, each one with an area of 10 m^2, were selected to perform the experimentation. The sub-plots worked as control areas, where all the inputs were carefully quantified and the conditions were maintained the same as in the main plots.

3.3.1. Soil hydraulic characterization

For the sandy soil, the unsaturated hydraulic conductivity, $K(h)$, and the water retention curve, $\theta(h)$, were determined in situ for the three soil layers 0–25, 25–55 and >55 cm. The internal drainage flux, first without evaporation at the soil surface and then with evaporation (Klute, 1986) were used to determine $K(h)$. Saturated conductivity, K_s, for both matrix and macropores, was determined using a method for layered soils based upon a ponded infiltration experiment as described in Timlin et al. (1994). For the silty loam, $\theta(h)$ was obtained using in situ data from an internal drainage experiment as described in Cameira et al. (2000), and laboratory data from the suction and pressure plate methods using undisturbed soil samples collected near the experimental sub-plots (Klute, 1986). $K(h)$ was obtained on undisturbed soil samples using the constant head permeameter for K_s and the crust and the hot air methods for $K(h)$ (Bouma et al., 1971; Arya et al., 1975). As in the sandy soil, three soil layers (0–25, 25–55 and >55 cm) were characterized by this methodology.

Table 2
Measured physical properties of the soils in the experimental plots

Depth (cm)	Particle size (%)				Bulk density	θ_v (%)			
	Coarse sand	Fine sand	Silt	Clay		2 kPa	10 kPa	32 kPa	1500 kPa
Silty loam soil (Eutric Fluvisol)									
0–25	1.5	54.2	27.9	16.4	1.43	39.9	36.6	33.1	11.4
25–50	1.4	53.8	28.0	16.8	1.55	39.7	36.0	32.2	12.4
50–80	1.6	56.1	25.2	17.1	1.58	38.2	35.1	33.5	12.3
Sandy soil (Eutric Cambisol)									
0–15	76.9	15.7	5.2	2.2	1.41	24.5	14.6	9.8	2.5
15–30	59.6	31.8	6.7	1.9	1.54	26.9	13.96	9.7	2.9
30–60	67.4	25.0	5.1	2.5	1.50	18.8	10.6	7.2	1.6

θ_v = volumetric soil water content.

The soil hydraulic properties were described by the functional forms suggested by Brooks and Corey with slight modifications (Ahuja et al., 1999b):

– the soil water content, θ ($cm^3\,cm^{-3}$) vs. soil water pressure head, h (cm) relation is expressed by

$$\theta(h) = \theta_s - A|h| \quad 0 \le |h| \le |h_{b1}| \tag{16a}$$

$$\theta(h) = \theta_r + B|h|^{-\lambda} \quad |h| \ge |h_{b1}| \tag{16b}$$

where θ_s is the saturated water content, θ_r is the residual content, h_{b1}, A, B and λ are parameters derived from best fitting of experimental data.

– the hydraulic conductivity, K ($cm\,h^{-1}$), vs. soil water pressure head, h (cm) relation is expressed by

$$K(h) = K_s|h|^{-N_1} \quad 0 \le |h| \le |h_{b2}| \tag{17a}$$

$$K(h) = C|h|^{-N_2} \quad |h| \ge |h_{b2}| \tag{17b}$$

where K_s is the field saturated hydraulic conductivity and h_{b2}, N_1, N_2, and C are parameters derived from experimental data.

Macroporosity, macropore sizes, and macropore conductivity were estimated for the silty loam soil using a tension infiltrometer similar to those described by Ankeny et al. (1988) but with the infiltration disc separated from the water reservoir. Details of the experiment can be found in Cameira et al. (2003b).

3.3.2. Crop measurements

The phenological stages of grain and forage corn were determined by observation of the crop development. The stages considered were crop emergence, three to four leaves, eight leaves, 12 leaves and maturation (ripening). At the beginning of each stage, six plants were collected in each sub-plot, and plant height, LAI, biomass per plant parts, and rooting depth were measured. The yield was determined at harvest.

3.3.3. Water balance measurements

Field monitoring of the variables related to the water balance started in June 1996 for the silty loam plot and in May 1997 for the sandy plot. Three replication sub-plots were identically instrumented with a neutron probe access tube installed down to 2.0 m, and a set of mercury tensiometers installed at 15, 30, 45, 60 and 90 cm in the silty loam plot, and at 10, 20, 30, 45, 60, 75 and 90 cm in the sandy plot. The soil water content was measured with a neutron probe at the above depths, and using the gravimetric method at 0–15 cm. Measurements were performed with a frequency not less than three times a week. An observation well was installed in the silty loam soil. The water table depth was recorded twice a week. All measurements were also performed before and 24 h after each irrigation.

3.3.4. Meteorological data

Precipitation and meteorological variables were required to determine the reference evapotranspiration (ETo), defined as the evaporation of an hypothetical crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. These variables, which are minimum and maximum air temperatures, wind velocity, relative humidity and incoming short wave radiation, were collected at the weather station of the experimental farm. ETo was computed daily using the FAO Penman–Monteith method (Allen et al., 1998).

3.4. Data analysis—water balance

As described in Section 3.1, evapotranspiration and fluxes through the bottom boundary are necessary for the control of the calibration process. As these variables are not measured directly in the field, their calculation is described in the following paragraphs.

Due to the different hydraulic behavior of the studied soils, two distinct approaches were used. In the silty loam soil, a finite difference approach of the soil water balance equation was applied to estimate the water balance terms for all soil layers with thickness Δz

$$S_n\Delta z_n = \left(\frac{\partial\theta}{\partial t}\right)_n \Delta z_n + \left(K(h)_{i-1}\left(\frac{\partial H}{\partial z}\right)_{i-1} - K(h)_{i+1}\left(\frac{\partial H}{\partial z}\right)_{i+1}\right) \tag{18}$$

where t is the time, z is the depth, n identifies the soil layer, i is the index of the layer boundary, S_n is the root water uptake, Δz_n is the layer thickness, θ is the soil water content, $K(h)$ is the hydraulic conductivity as a function of pressure head and H is the hydraulic head. The soil water fluxes in Eq. (18), φ_z, are computed at the boundaries of each layer using the generalized Darcy equation. For the first layer they include rainfall, irrigation and/or soil evaporation at the soil surface.

Eq. (18) was solved for the days when θ and H were measured and for the soil layers with boundaries at depths of 0, 22.5, 37.5, 52.5, 67.5, 82.5 and 97.5 cm. Cubic splines were fitted to the observed $\theta(z,t)$ and $H(z,t)$ to determine the gradients of $\theta(t)$ at the centre of the layers and $H(z)$ at the boundaries of the layers. Time intervals including an irrigation or rain event were not considered in the computations of gradients of $\theta(t)$ because of the strongly nonlinear variation of soil water content which would induce significant errors in the calculation of $\theta(t)$ gradients. The hydraulic conductivity at the interfaces of the layers was determined by the geometric mean of the $K(h)$ value, calculated from h observed at the center of both layers. For days without observations in between rain or irrigation events, the soil water fluxes at the bottom of the root zone were obtained by linear interpolation between the fluxes calculated for the days with observations. The evaporation flux through the soil surface was estimated using the parametric model of Ritchie (Ritchie and Burnett, 1971). ETc was computed by summing the $S_n \Delta z_n$ values computed for each layer with Eq. (18) for the entire soil profile. The ratio ETc/ETo was then calculated. For the days without measurements, the ratio ETc/ETo was obtained by linear interpolation between days with observations, and ETc was estimated as the product of this ratio and ETo.

For the sandy soil the water balance was performed using a simplified form of the water balance equation, representing the integration of all terms for a period of time, Δt, and for the rooting depth, z_r

$$P + I = \mathrm{ETc} + \Delta W + \varphi_m \Delta t \tag{19}$$

where P is the precipitation, I is the irrigation, ETc is the crop evapotranspiration, ΔW is the change in water storage in the root zone and $\varphi_m \Delta t$ is the water flowing through the bottom boundary (drainage or upward flow). All terms are in mm.

Due to frequent wettings, the hydraulic gradients in the sandy soil change very quickly. For these conditions, the use of Eq. (18) could be associated with high errors in the calculation of soil water fluxes when H and θ are not monitored very frequently after an irrigation or rainfall event. Thus, vertical discretization of the soil profile in layers is not advised and Eq. (19) was applied to the total soil profile, i.e. between the soil surface and the depth of 82.5 cm, for time intervals Δt between irrigation or rain events, to determine the average ETc during these periods. The average soil water flux at the bottom boundary was calculated as follows: (1) the hydraulic conductivity and the hydraulic gradients were calculated from observations of H at 75 and 90 cm depths; (2) the soil water fluxes φ (mm day^{-1}) were determined at 82.5 cm depth by the Darcy's equation, and the average flux, φ_m, for the interval $\Delta t = t_{j+1} - t_j$, was calculated as $\varphi_m = (\varphi_{t_j} + \varphi_{t_{j+1}})/2$, where j refers to time. The ratio ETc/ETo was determined and

Table 3
Brooks and Corey parameters fitted for the silty loam soil

ΔZ (cm)	θ_r (cm^3 cm^{-3})	θ_s	λ	h_{b1} (cm)	A	K_s (cm day^{-1})	N_1	h_{b2} (cm)	C (cm day^{-1})	N_2
From field measurements										
0–25	0.05	0.404	0.262	84.0	0.0007	9.12	0.00	1.0	9.13	1.33
25–50	0.06	0.386	0.265	106.0	0.0004	21.4	0.00	1.0	21.4	1.39
>50	0.05	0.379	0.207	59.5	0.0004	106.4	1.91	14.9	18.9	1.27
After calibration										
0–10	0.05	0.462	0.400	46.8	0.0014	24.0	0.00	1.0	24.0	1.33
10–20	0.05	0.420	0.300	64.8	0.0008	24.0	0.00	1.0	24.0	1.33
20–35	0.05	0.400	0.262	92.2	0.0007	24.0	0.00	1.0	24.0	1.33
35–50	0.06	0.386	0.265	106.0	0.0005	21.4	0.00	1.0	21.4	1.39
50–65	0.05	0.390	0.207	65.5	0.0005	34.0	1.91	14.9	18.9	1.27
80–150	0.05	0.390	0.207	65.5	0.0005	34.0	1.91	14.9	18.9	1.27

Table 4
Macropore properties for the silty loam

ΔZ (cm)	Field measurements	After calibration	
	M_{ac} ($cm^3\ cm^{-3}$)	M_{ac} ($cm^3\ cm^{-3}$)	M_d (%)
0–35	94×10^{-6}	2×10^{-3}	0.8
>35 cm	1×10^{-6}	2×10^{-4}	0.6

interpolated for the days out of the calculation period to estimate ETc by multiplying ETc/ETo by ETo.

4. Results and discussion

4.1. Calibration of the soil hydraulic properties

For both soils the calibration of the hydraulic properties showed the necessity to subdivide the soil profile into more layers than originally.

The calibration of the hydraulic properties for the silty loam soil resulted in a system with two domains of flow: macropore flow between the soil surface and the plough pan located at 30 cm, and matrix flow. Table 3 shows the Brooks and Corey parameters for the soil matrix before and after calibration. A calibration of soil matrix properties was required to achieve accurate infiltration and redistribution results. The calibrated macropore properties involved changes in macroporosity, and hence conductivity, as well as division of macroporosity into continuous and dead end fractions with depth (Table 4). The main changes occur in the upper layers. Differences in the parameters of the $\theta(h)$ function were due to the new layering. Differences in K_s are due to the sampling methods, which cause some compaction, especially in the ploughed layer, destroying macroporosity. The tension infiltrometer apparently does not distinguish between continuous and dead-end macropores, and does not give any indication about the continuity of macropores with depth. Detailed description of these results can be found in Cameira et al. (2000).

The sandy soil is well represented by a one-domain system with a homogeneous matrix, a high saturated conductivity and rapid drainage. The Brooks and Corey parameters, before and after calibration for the soil matrix are presented in Table 5. The process was based upon the decrease of the parameter N_2, which is the slope of the second part of the $K(h)$ curve. This corresponded to increased drainage for smaller soil water pressures.

4.2. Calibration of the crop model

Table 6 shows the phenology and the site-specific parameters determined for grain and forage corn. Because forage corn has a shorter cycle when compared with grain corn, differences are found in the number of days necessary for the beginning of the four leaf and the reproductive stages. In the forage corn system N availability seemed to be limiting the crop development. Good results for the biomass, plant N content and N in the soil, were only achieved by lowering the maximum active nitrogen uptake in relation to a situation where nitrogen is not limiting the system. For these limiting conditions Hanson (1999) advises the use of a value between 1.5 and 1. Parameters 8 and 9 were higher for grain corn reflecting, as expected, a higher ratio between grain yield and total above ground biomass in comparison

Table 5
Brooks and Corey parameters fitted for the sandy soil

ΔZ (cm)	θ_r ($cm^3\ cm^{-3}$)	θ_s	λ	h_{b1} (cm)	A	K_s (cm day^{-1})	N_1	h_{b2} (cm)	C (cm day^{-1})	N_2
From field measurements										
0–25	0.00	0.39	0.63	25.1	0.0024	444.8	0.05	52.4	3.2×10^{10}	4.6
25–55	0.00	0.37	0.68	35.5	0.0009	444.8	0.05	79.4	1.9×10^{15}	6.8
>55	0.00	0.37	0.80	56.2	0.0010	166.6	0.08	120.2	1.7×10^{15}	6.3
After calibration										
0–10	0.00	0.39	0.59	18.0	0.0024	444.8	0.05	16.95	1×10^{6}	4.2
10–20	0.00	0.36	0.59	23.2	0.0009	444.8	0.05	16.95	1×10^{6}	3.8
20–50	0.00	0.36	0.96	69.1	0.0010	444.8	0.02	60.31	8×10^{11}	6.0
>50	0.00	0.36	0.93	79.2	0.0010	166.6	0.02	91.74	3×10^{12}	6.0

Table 6
Beginning of the phenological stages, simulated and measured

Stage	Grain corn		Forage corn	
	Measured	Simulated	Measured	Simulated
Emergence	01/07	01/07	28/04	22/04
4 Leaves	14/07	19/07	17/05	15/05
12 Leaves	02/08	08/08	26/06	28/06

with forage corn. Calibration of biomass seemed to be more sensitive to the specific leaf density (amount of biomass needed to obtain a LAI of one) than to the other site-specific parameters. The same response was found by users from the MSEA project (Hanson, 1999). Thus in future work, when new crops are being simulated, this parameter should be measured in the field.

Although it is difficult to pinpoint the beginning of a certain development phase, since plants in a field are not homogeneous, Table 6 shows that the model simulates the beginning of each stage reasonably for both grain corn and forage corn.

Using the calibrated site specific crop parameters instead of the default values decreased the LAI simulation error from 85 to 14.4% and from 90 to 13.9% for grain corn and forage corn, respectively. Simulated LAI after calibration and the corresponding measured values are shown in Fig. 2. For the above ground biomass the simulation error decreased with the calibration from 20 to 3.2% and from 22 to 2.2% for grain corn and for forage corn, respectively. Table 7 shows the errors associated with the simulations of crop development after calibration and the corresponding residual analysis. Simulated plant height, LAI, total biomass and its distribution according to different plant parts, had RMSE's lower than the MSD of the measured data. Differences between simulated and measured values were always below 15% as recommended by the model developers.

4.3. Calibration of the evapotranspiration model

After the calibration of the crop development model, a preliminary run of the model was performed, using a stomatal resistance, r_{st}, of 225 s m^{-1}, together with a soil resistance, r_s^s, of 100 s m^{-1} (which is compatible to a humid but not wet soil). The model is only slightly sensitive to the mean boundary resistance, r_b, thus a general average value of 25 s m^{-1}, as indicated by Shuttleworth and Wallace (1985), was used.

The comparison between measured and simulated evapotranspiration values is presented in Fig. 3. It can be clearly seen that the model has a tendency to overestimate ETc, which agrees with the results published by Farahani et al. (1996). The RMSE of the cumulative ETc was higher than the MSD. The fact that in the original RZWQM formulation the bulk stomatal resistance of the canopy, r_s^c, is not constrained is questionable. It has been long recognized

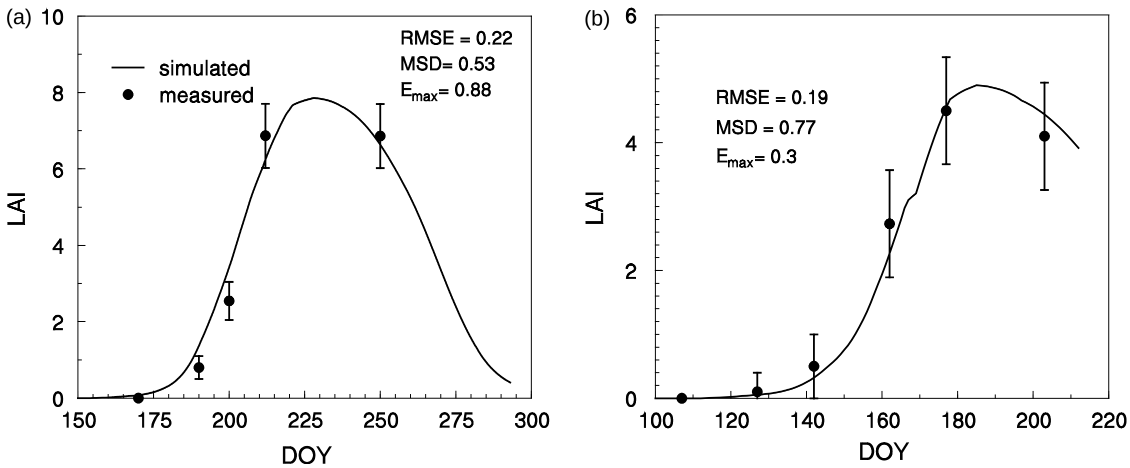

Fig. 2. Simulated and measured corn leaf area index (LAI) vs. days of the year (DOY): (a) silty loam soil; (b) sandy soil (calibration phase).

Table 7
Cumulative values for some control variables used for the plant model and associated simulation errors

Control variable	Measured	Simulated	Error (%)[a]	RMSE	MSD	E_{max}
Grain corn—silty loam soil						
LAI max	6.87±0.84	7.9	14.4	0.22	0.53	0.88
Tot biom (ton/ha)	23.07±3.29	22.3	3.2	0.6	1.6	3.9
Leaves	3.4±0.9	3.0	−11.8	0.3	0.7	0.7
Stalks	7.5±0.01	7.9	6	0.4	0.7	1.5
Yield-grain (ton/ha)	12.17±1.2	11.3	−7.5			
Forage corn—sandy soil						
LAI max	4.3±0.18	4.9	13.9	0.19	0.77	0.3
Tot biom (ton/ha)	18.5±2	18.9	2.2	0.3	1.6	2.3
Leaves	1.9±0.4	2.1	10.5	0.6	1.3	0.95
Stalks	16.6±1.1	16.8	1.2	0.3	1.6	2.3
Yield (ton/ha)	18.5±2	18.9	2.2			

[a] Error = [(simulated value − measured value)/measured value] × 100.

that once effective soil cover is reached water use by the crop becomes independent of LAI and remains stable, which is indicated by a 'plateau' on the crop coefficient curve (Wright, 1981; Doorenbos and Pruitt, 1977; Allen et al., 1998). Effective soil cover is obtained at 70–80% soil coverage (Doorenbos and Pruitt, 1977; Hatfield, 1989), which corresponds, as far as the corn crop is concerned, to a LAI of 2.7 (Ritchie and Burnett, 1971). Results in Fig. 4 clearly demonstrate this behavior and confirm that a LAI close to 3 effectively marks the turn to a full canopy. So, an alteration to Eq. (11) was introduced, LAI was replaced with LAI_{eff} defined as:

$$LAI_{eff} = LAI, \quad LAI \leq 3 \tag{20}$$

$$LAI_{eff} = 3, \quad LAI > 3$$

This alteration affects only the mid-season and ripening stages, where overestimation has been previously identified. The new results are then presented in Fig. 5, showing that this simple change induced a considerable improvement in the model performance, not only in precision (as indicated in the increase in the coefficient of determination) but also in accuracy (slope of the regression line close to 1). The RMSE of ETc simulation decreased by 51%. Fig. 5(b) more clearly illustrates the effect the new formulation has on correcting the ETc overestimation by the model after the crop has reached full growth. The change in the definition of LAI_{eff}, as given by

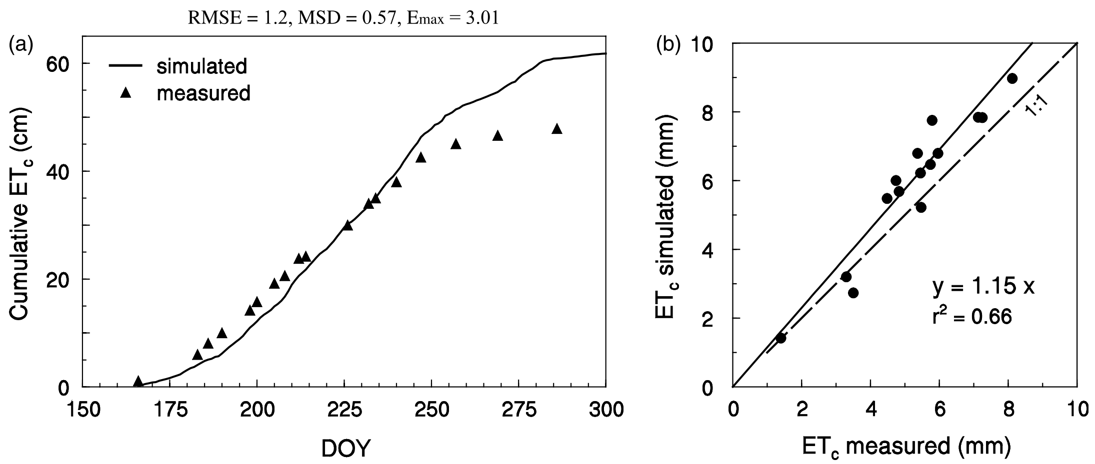

Fig. 3. ETc measured and simulated for the silty loam soil before calibration of the ETc module: (a) cumulative values, (b) simulated/measured daily ETc.

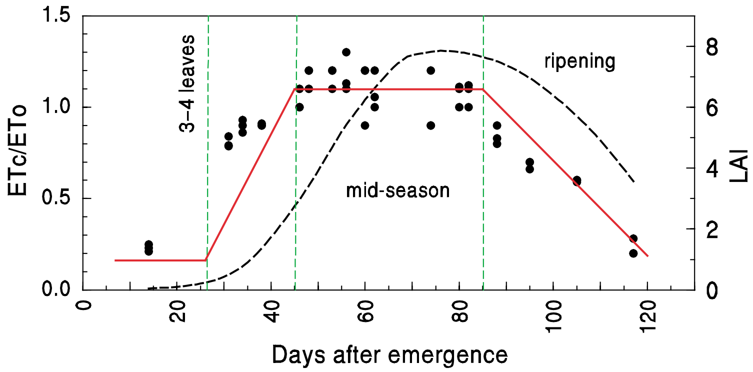

Fig. 4. Measured crop coefficient, ETc/ETo (●) and its comparison with the basal crop coefficient (—) determined using the methodology proposed by Allen et al. (1998). Superimposed on the graph is the evolution of LAI throughout the crop growth period (- - -).

Eq. (20), and described in detail in Alves and Cameira (2002) has subsequently been incorporated in the most recent version of RZWQM.

The simulated root water uptake (S) by soil layer is shown in Fig. 6. The RMSE of the simulation is lower than the MSD between soil surface and the depth of 52.2 cm. The opposite occurs below this depth, where the model overestimates root uptake. The cause for these maybe related with parameter $R_a(z)$ in the sink term of the Richards equation [Eq. (2)], which determines the proportion of active roots in each soil layer. R_a is an output of the plant growth model. This output was not checked since there were no field data. Nevertheless this result did not compromise the simulation of soil water since at this depth root extraction is very small. For the same reason the cumulative root uptake for the entire profile presented a small error of 17.7% (Table 8).

As a result of the good model performance regarding the water movement in the soil profile and ETc, the simulation of soil moisture evolution with time and depth gave satisfactory results (Fig. 7). Similarly good results were obtained for the water fluxes through the bottom boundary of the root zone (Fig. 8). The cumulative values for the simulated

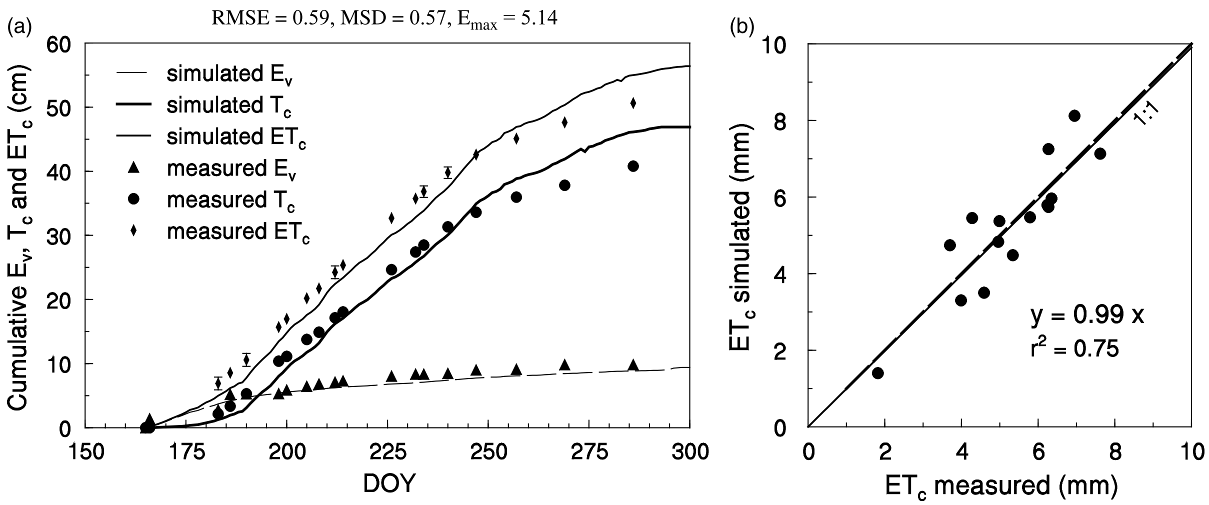

Fig. 5. ETc measured and simulated for the silty loam soil after calibration: (a) cumulative values of E_v, T_c and ETc, (b) simulated/measured daily ETc.

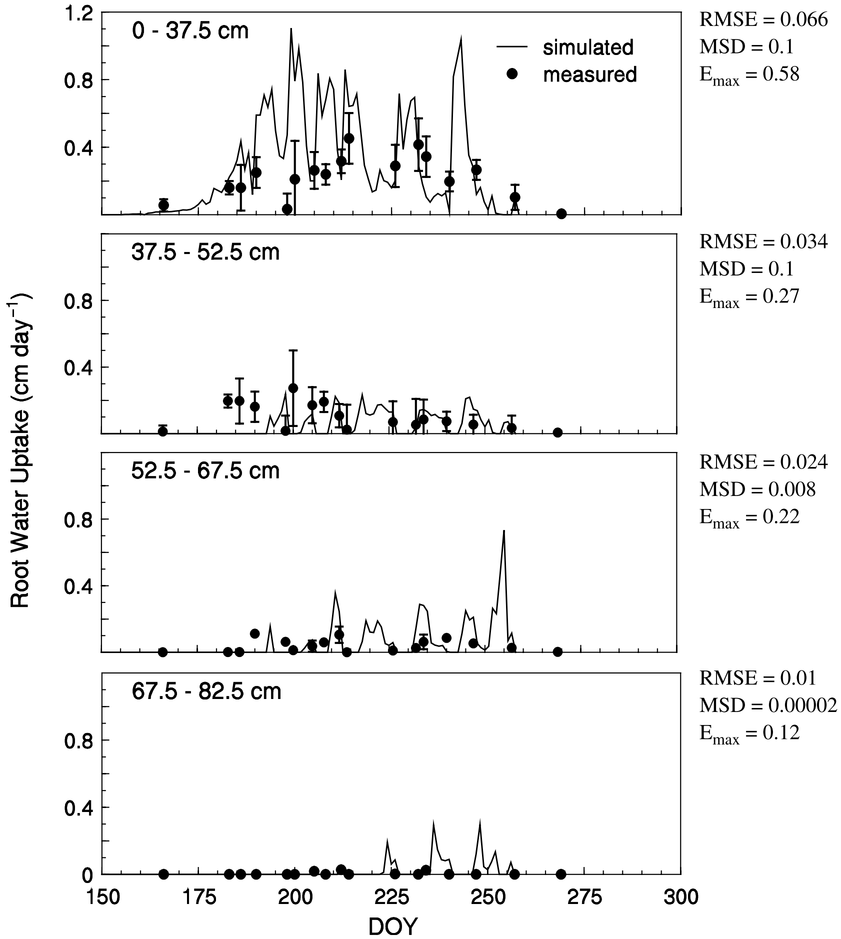

Fig. 6. Simulated and measured root uptake by soil layer for the silty loam soil (calibration phase).

water table contribution (capillary rise) presented an error of 4.9%, with the RMSE being lower than the MSD of the measurements.

Table 8 presents a summary of some simulated and measured hydrological variables for the silty loam soil. After calibration of the soil hydraulic properties, the hydrologic (soil water and evapotranspiration) and crop development models, the RZWQM was able to adequately simulate the plant and water related processes occurring in the silty loam system.

For the sandy soil, the soil water balance method used to calculate ETc produced average values for the few periods with no irrigation or rain events. For this reason the measured cumulative ETc presented in Fig. 9 was calculated using daily ETc values calculated from the water balance together with the crop coefficient method (Dorenboos and Pruit, 1977). Because these values were calculated and not measured, the cumulative ETc was not considered as a control variable for

Table 8
Errors in the simulation of some hydrological variables, silty loam soil

Variable (cm)	Measured	Simulated	Error (%)
Capillary rise	20.4 ± 0.79	21.4	4.9
Root uptake	35.8 ± 1.1	41.9	17.7
Evaporation	9.1	8.4	−7.6
Residual storage	25.6 ± 1.3	26.7	4.3

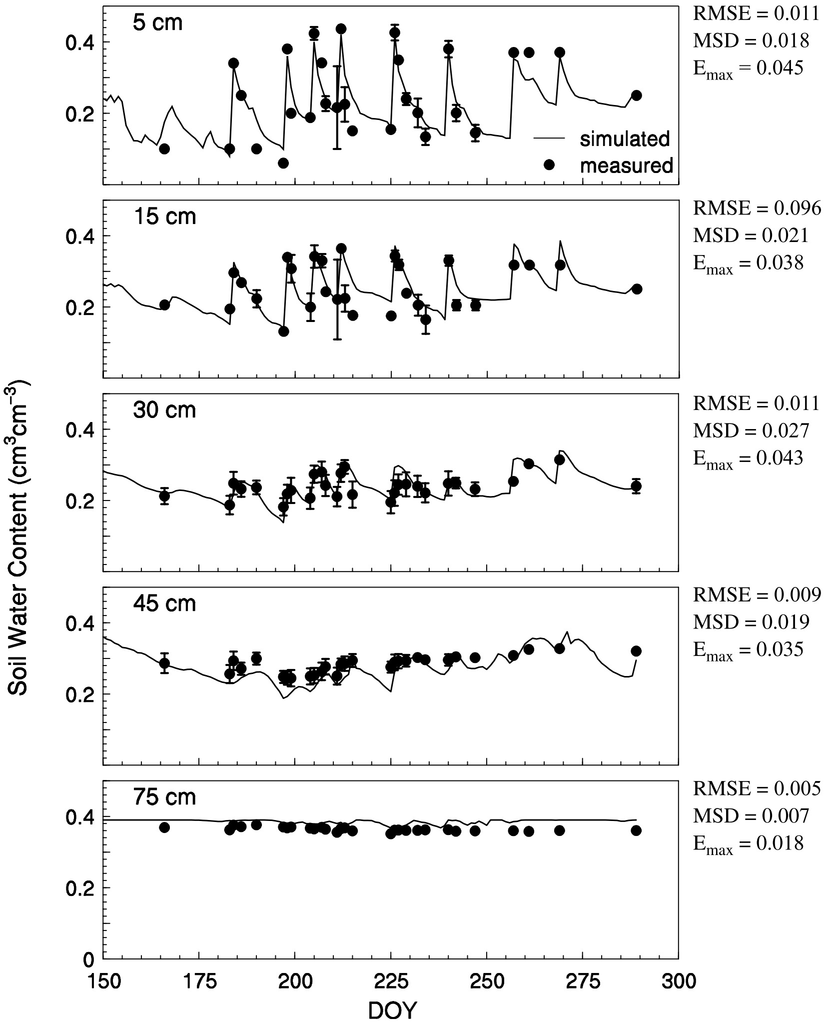

Fig. 7. Simulated and measured soil water for the silty loam soil (calibration phase).

the evaluation but to qualitatively evaluate the simulated tendencies.

The same happened with the drainage rate calculated only for the measurement days using Darcy's equation. Due to frequent sprinkler irrigation and rapid drainage through the bottom layer, it was not possible to estimate drainage values for the other days. Fig. 10 shows the drainage flux calculated from Darcy's law for the days with measurements and simulated drainage flux for the entire crop season. The standard deviation associated with the computed average is high, thus indicating large uncertainties resulting from the use of the Darcy equation for the calculation of water fluxes in this type of soil. Besides soil heterogeneity, this uncertainty is due to the high hydraulic conductivity of this soil, which magnifies the error of the flux estimates when a small error occurs in the estimation of the hydraulic gradient. The control variables for the hydrology component were then the effective pressure and the soil water content for the different soil layers.

For the effective pressure simulations (Fig. 11) the RMSE of the simulations was lower than the MSD until the depth of 45 cm. Below this depth the simulation error increased. The RMSE for the soil moisture

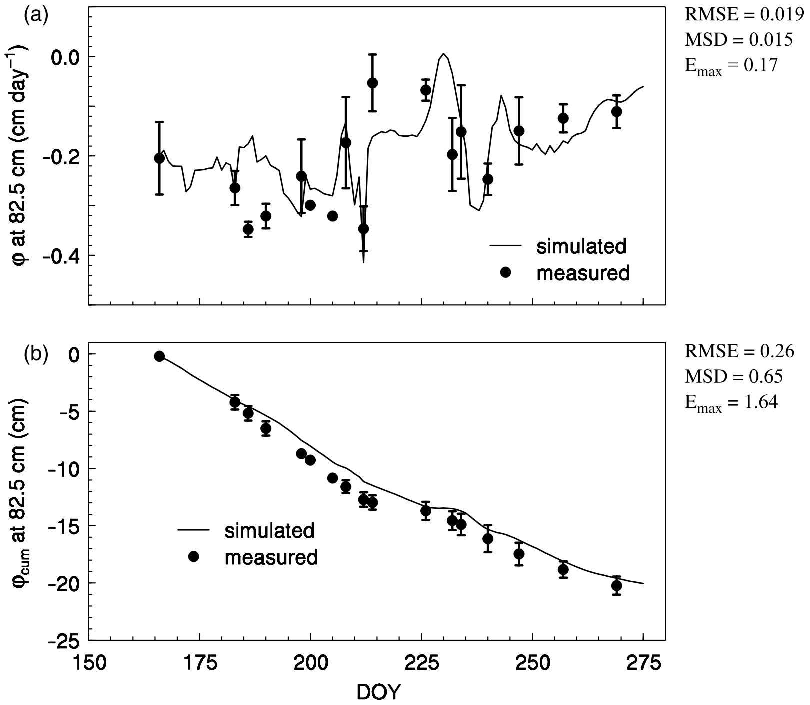

Fig. 8. Simulated and measured evolution of the fluxes (φ) through the bottom boundary of the silty loam soil: (a) daily values and (b) cumulative values (calibration phase).

simulations (Fig. 12) was lower than the MSD for the entire profile indicating a good description of the water related processes by the model.

As can be seen in Table 9, which presents a summary of hydrologic variables for the sandy soil, evapotranspiration and final water storage in the soil were simulated with an acceptable precision.

4.4. Validation

Table 10 shows the model predictions for the length of the phenological stages for the two corn varieties. The global accuracy of the predictions is good, with the exception of the four-leaf stage. However, the 23% error is acceptable in practical applications for complex and spatially variable crop conditions in a field. The error did not appear to influence the predictions of LAI, biomass and yield as shown in Table 11. As in the calibration phase, LAI is the crop variable associated with a higher error. The prediction of soil moisture during the 1998 season for the silty loam soil is shown in Fig. 13, and the residual analysis of the results is presented in Table 12. Modeling efficiency (EF) approached the expected value of one at the surface, decreasing with depth but always high until 45 cm. This means that the model explains in a large portion the variability of measured data. EF decreases below 60 cm.

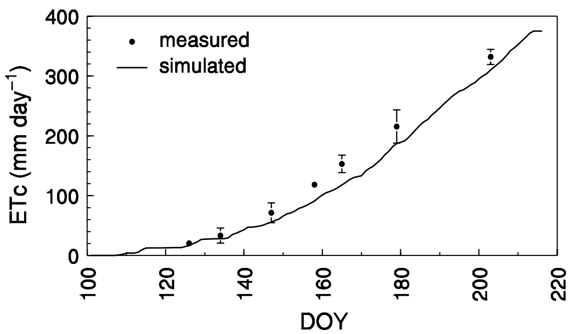

Fig. 9. Measured and simulated cumulative crop evapotranspiration for the sandy soil (calibration phase).

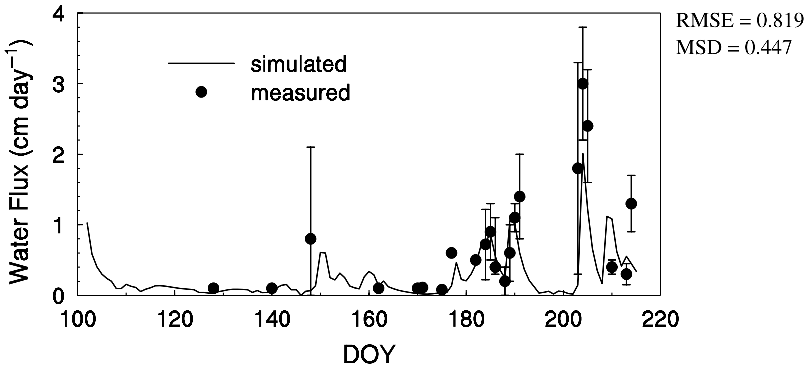

Fig. 10. Simulated and measured drainage fluxes at the bottom of the root zone, sandy soil (calibration phase).

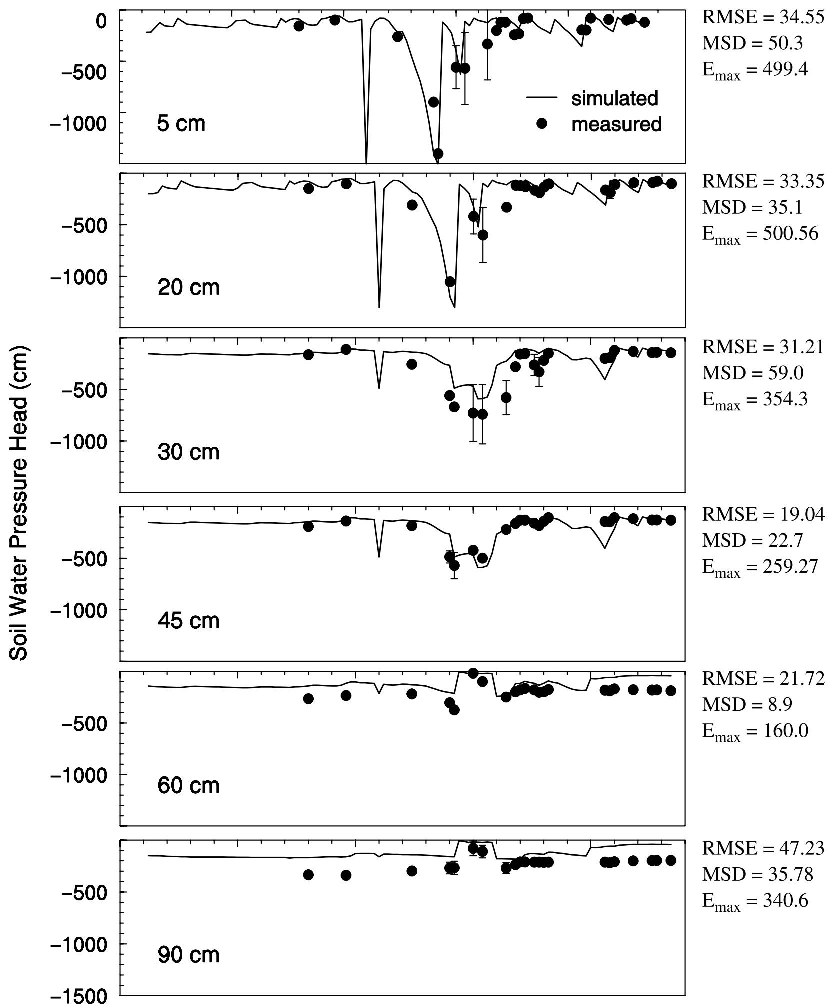

Fig. 11. Simulated and measured effective soil water pressure head by soil layer. Sandy soil (calibration phase).

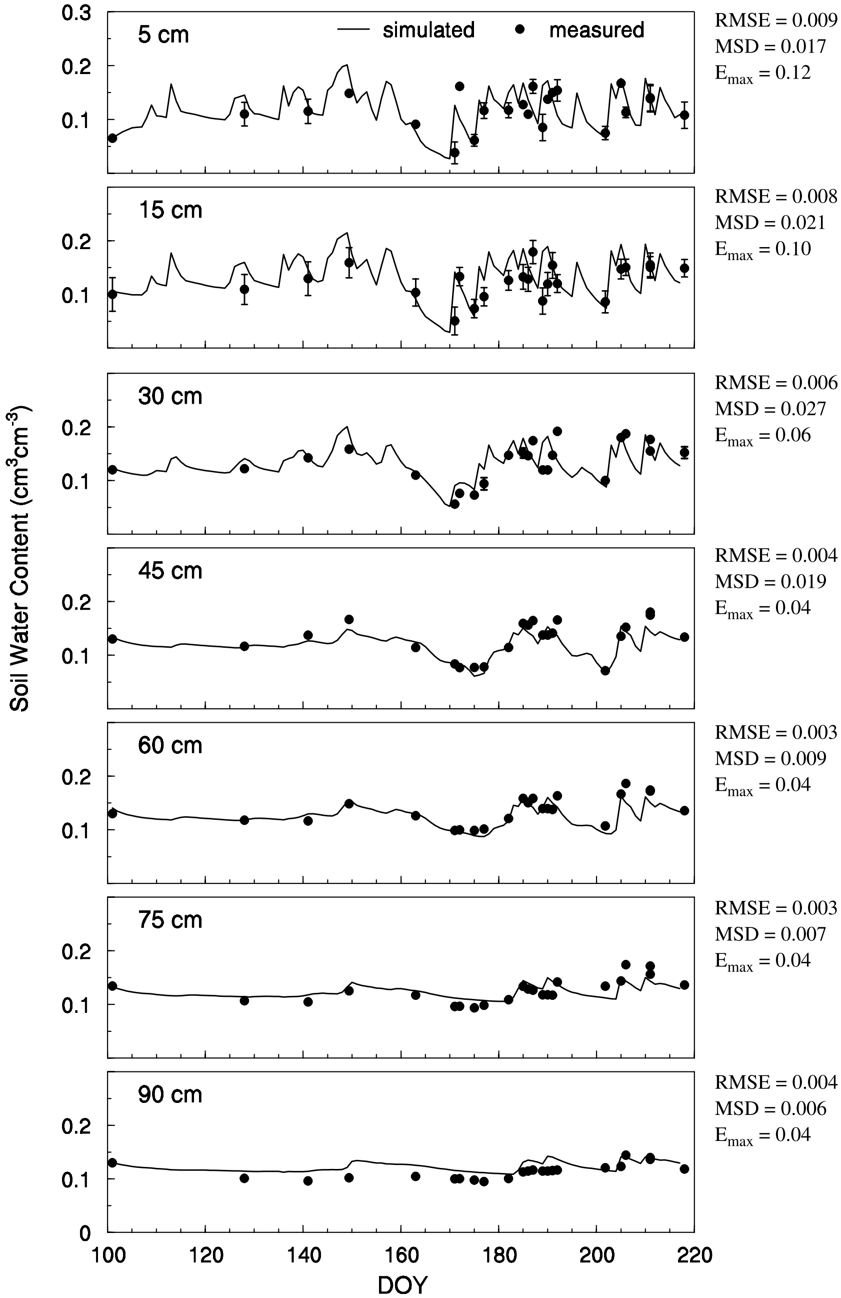

Fig. 12. Simulated and measured soil water content for the sandy soil (calibration phase).

As shown in Fig. 13 measured soil moisture at these depths was relatively constant in time, thus reducing the term $(O_K - \bar{O})$ in Eq. (14) and thus decreasing EF. This reinforces the conclusion that EF is a good indicator only when the variable presents large variations in time. Water storage in the root zone at the end of the crop cycle was predicted with an error of 5.9%.

Fig. 14 shows model predictions for soil moisture for the sandy soil and Table 13 shows

Table 9
Errors in the simulation of some hydrological variables, sandy soil

Water balance term (cm)	Measured	Simulated	Error (%)
Evapotranspiration	34.2	36.2	6
Final storage in the soil	10±5.1	7.9	−21

Table 10
Predicted and observed length (days) for each crop stage

Crop stage	Grain corn			Forage corn		
	Measured	Predicted	Error (%)	Measured	Predicted	Error (%)
Seeding-emergence	7	7	0	9	10	11
Emergence-4 leaves	27	28	3.7	37	38	3
4 Leaves–12 leaves	42	52	23	60	62	3

the corresponding residual analysis. Again EF shows higher values above the depth of 60 cm. Water storage at the end of the crop cycle was predicted with an error of 8.2%.

Considering that the errors associated with the neutron probe measurements are between 1 and 2% (Haverkamp et al., 1984) the low values found for ME and RMSE are also indicating that the model is predicting soil moisture evolution in time and depth with accuracy.

The model predictions presented above were obtained for climatic conditions different from the ones used for the calibration process. Irrigation and fertilization management practices were also distinct. Considering that for the validation the parameters calibrated previously describing the crop, the soil and the water were used without changes, and that the prediction errors are similar to the ones obtained after the calibration procedure, it can be concluded that the model predicted crop development, yield and the soil water balance terms with an accuracy that is acceptable in practical applications for complex and spatially variable field conditions.

5. Conclusions

The RZWQM is a complex model that requires a large amount of input data to characterize the system to be modeled. As was shown in the present study, each time a model is used in a new region, the model has to be globally calibrated. In fact it was necessary to calibrate the different modules in order for the model to predict, with accuracy, crop development, yield and the water balance terms for the studied systems. The iterative methodology used for calibration was appropriate to better account for the strong interactions among plant development, evapotranspiration, root uptake and soil water. Calibration of the soil hydraulic properties obtained from measurements was necessary for the simulation of the observed infiltration times and depths.

After the calibration of the site specific crop parameters, the simulation errors for LAI decreased from 85 to 14.4% and from 90 to 13.9% for grain corn and forage corn, respectively. For the above ground biomass the simulation error decreased from 20 to 3.2% and from 22 to 2.2% for grain corn and for forage corn, respectively.

The sink term in the Richard's equation corresponding to the root extraction determines in great extent the goodness of the simulation of the soil water profiles. Good simulation of this sink is highly dependent upon the evapotranspiration calculations. The calibration of the stomatal and soil resistances by

Table 11
Measured and predicted crop properties for grain and forage corn

Variable	Grain corn			Forage corn		
	Measured	Predicted	Error (%)	Measured	Predicted	Error (%)
LAI	6.5±0.6	7.6	17	5.5	4.8	−12.7
Total biomass (Mg ha^{-1})	22±4.3	22.5	2.3	17.8	18.3	2.8
Yield (Mg ha^{-1})	11.2±2	11.3	1.1	17.8	18.3	2.8

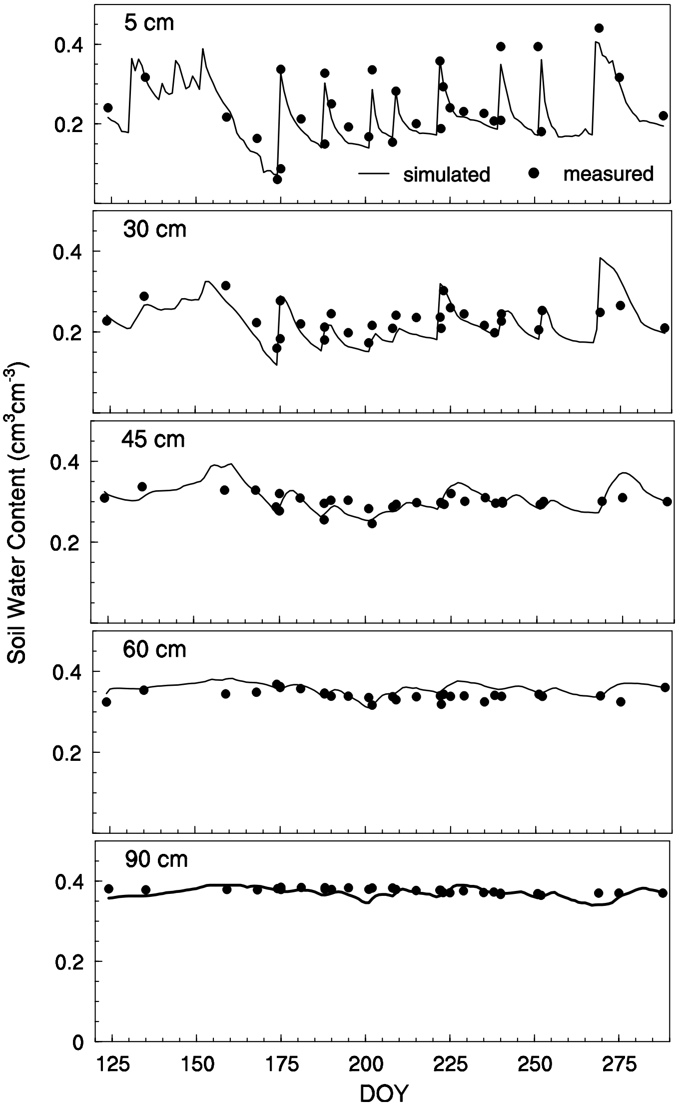

Fig. 13. Predicted and measured soil water content for the silty loam soil. (Validation phase).

Table 12
Residual analysis for the prediction of soil water, silty loam soil

Depth (cm)	ME ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)	EF (%)
5	0.0491	0.0185	0.95
30	0.0829	0.0228	0.74
45	0.0583	0.0230	0.49
60	0.0391	0.0152	0.24
90	0.0294	0.0099	0.27

Table 13
Residual analysis for the prediction of soil water, sandy soil

Depth (cm)	ME ($cm^3\ cm^{-3}$)	RMSE ($cm^3\ cm^{-3}$)	EF
5	0.054	0.027	0.69
30	0.179	0.054	0.72
45	0.129	0.037	0.56
60	0.123	0.038	0.39
90	0.085	0.034	0.07

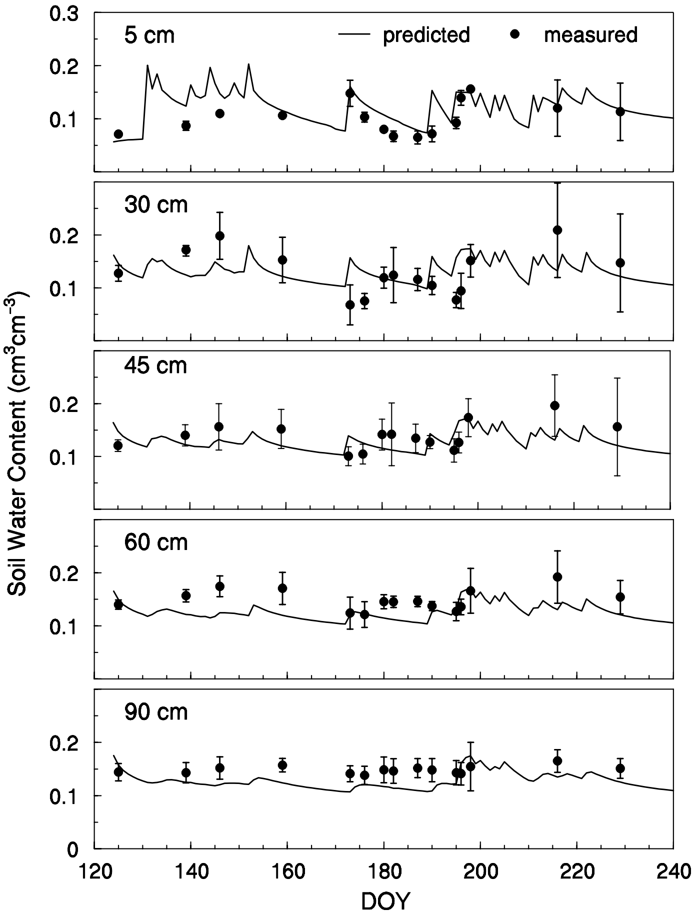

Fig. 14. Predicted and measured soil water content for the sandy soil. (Validation phase).

itself was not sufficient for a good simulation of ETc. This calculation module has revealed some weaknesses. This study has shown that a simple modification to the definition of effective leaf area, restricting the bulk canopy resistance after complete cover by the crop, could greatly improve estimates. The usefulness of this change has been acknowledged subsequently by being incorporated in the currently available version of RZWQM. The evapotranspiration model was very sensitive to plant development requiring the knowledge of the field LAI to control the simulations. The site-specific parameter, specific leaf density, which reflects the amount of plant biomass per unit LAI, is the most sensitive parameter in the crop growth model so it is advised that it should be measured in the field.

During validation, crop yield was predicted with an error of 1.1 and 2.8% for grain and forage corn, respectively. For the silty loam soil the evolution of soil water was predicted with an efficiency ranging from 95 to 27% between the soil surface and the depth of 90 cm. For the sandy soil the prediction efficiency ranged between 69 and 7% between the soil surface and the depth of 90 cm. These results indicate that, for the agricultural fields under study, the model is able to simulate climatic and management conditions different from the ones used for the calibration with an accuracy that is acceptable in practical applications for complex and spatially variable field conditions. However, for the quantification of the uncertainty to be expected, validation must be performed for a wider range of situations, including extreme climatic and management conditions. The next phase of the model application in this fields will be to screen different management scenarios in order to select the agronomic practices that are more adequate for these systems.

The model simulated two distinct bottom boundary conditions, which are an upward flux from a shallow water table in the silty loam soil, and a drainage flux in the sandy soil. The model was very sensitive to the bottom boundary condition in the cases when the water table was close to the root zone in result of both surface inputs (irrigation and precipitation) and subsurface lateral fluxes. The simulation results showed that the estimation of the water table behavior during the crop season is an input requirement of the model. For the studied conditions, where the fluxes are low and fairly constant, this estimation can be done based upon historical data, including wet and dry years. In a different system where the fluxes can change quickly during short periods (e.g. sandy soils with a shallow water table responding rapidly to precipitations) historical data may not be enough to characterize the water table behavior.

Concerning the crop development, the model seems to have a weakness for the situations where nitrogen availability is limited. At this time and under the advise of the model developers, if nitrogen limits the system the parameter nitrogen uptake rate must be set to an exceptionally low value (1–1.5) loosing its deterministic meaning. This discourages the user to apply the model to different fertilization management scenarios without changing a parameter that was previously calibrated.

References

Addiscot, T., Smith, J., Bradbury, N., 1995. Critical evaluation of models and their parameters. J. Environ. Qual. 24, 803–807.

Ahuja, L., DeCoursey, D., Barnes, B., Rojas, K., 1993. Characteristics of macropores studied with the ARS root zone water quality model. Trans. ASAE 36, 369–380.

Ahuja, L., Johnsen, K., Heathman, G., 1995. Macropore transport of a surface applied bromide tracer: model evaluation and refinement. Soil Sci. Soc. Am. J. 59, 1234–1241.

Ahuja, L., Ma, L., Rojas, K., Boesten, J., Farahani, H., 1996. A field test of the RZWQM simulation model for predicting pesticide and bromide behavior. J. Pestic. Sci. 48, 101–108.

Ahuja, L., Rojas, K., Hanson, J., Shaffer, M., Ma, L. (Eds.), 1999. RZWQM Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, CO, USA.

Ahuja, L., Johnsen, K., Rojas, K., 1999b. Water and chemical transport in soil matrix and macropores. In: Ahuja, L., Rojas, J., Hanson, M., Ma, L. (Eds.), RZWQM. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Colorado USA, pp. 13–50.

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper 56. FAO, Rome.

Alves, I., Cameira, M.R., 2002. Evapotranspiration estimation performance of root zone water quality model: evaluation and improvement. Agric. Water Manage. 57, 61–73.

Ankeny, M.D., Kaspar, T.C., Horton, R., 1988. Design for an automated tension infiltrometer. Soil Sci. Soc. Am. J. 52, 893–896.

Arya, L., Farrel, D., Blake, G., 1975. A field study of water depletion patterns in presence of growing soybean roots. I. Determination of hydraulic properties of the soil. Soil Sci. Soc. Am. J. 45, 1023–1030.

Bouma, J., Hillel, D., Hole, D., Amerman, C., 1971. Field measurements of unsaturated hydraulic conductivity by infiltration through artificial crusts. Soil Sci. Soc. Am. Proc. 35, 362–364.

Cameira, M.R., Sousa, P.L., Farahani, H.J., Ahuja, L., Pereira, L.S., 1998. Evaluation of the RZWQM for the simulation of water and nitrate movement in level-basin, fertigated maize. J. Agric. Eng. Res. 69, 331–341.

Cameira, M.R., Ahuja, L., Fernando, R.M., Pereira, L.S., 2000. Evaluating field measured soil hydraulic properties in water transport simulations using the RZWQM. J. Hydrol. 236, 78–90.

Cameira, M.R., Fernando, R.M., Pereira, L.S., 2003a. Monitoring water and NO_3–N in irrigated maize fields in the Sorraia Watershed. Portugal Agric. Water Manage. 60, 199–216.

Cameira, M.R., Fernando, R.M., Pereira, L.S., 2003b. Soil macropore dynamics affected by tillage and irrigation. Soil Till. Res. 70/2, 131–140.

Celia, M.A., Bouloutas, E.T., Zarba, R.L., 1990. A general mass-conservative numerical solution for the unsaturated flow equation. Water Resour. Res. 26, 1483–1496.

Doorenbos, J., Pruitt, W.O., 1977. Crop Water Requirements, FAO Irrigation and Drainage Paper 24. FAO, Rome.

Farahani, H., Ahuja, L., 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Trans. ASAE 39, 2051–2064.

Farahani, H.J., DeCoursey, D., 1999. Potential evaporation and transpiration processes in the soil–residue–canopy system. In: Ahuja, L., Rojas, K., Hanson, J., Shaffer, M., Ma, M. (Eds.), RZWQM, Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, CO, USA, pp. 51–75.

Farahani, H.J., Bausch, W.C., Aiken, R.M., Ahuja, L.R., 1996. Evapotranspiration in system-wide agricultural models. In: Camp, C.R. et al. (Ed.), Evapotranspiration and Irrigation Scheduling Proceedings of International Conference, San

Antonio, TX, 3–6 November, ASAE, St Joseph, MI, pp. 673–678.

Hanson, J.D., 1999. Generic crop production. In: Ahuja, L., Rojas, K., Hanson, J., Shaffer, M., Ma, M. (Eds.), RZWQM. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, CO, USA, pp. 81–118.

Hatfield, J., 1989. Aerodynamic properties of partial canopies. Agric. For. Meteorol. 46, 15–22.

Haverkamp, R., Vauclin, M., Vachaud, G., 1984. Error analysis in estimating soil water from neutron probe measurements: 1. Local standpoint. Soil Sci. 137 (2), 78–90.

Johnsen, K., Liu, H., Dane, J., Ahuja, L., Workman, S., 1995. Simulating fluctuating water tables and tile drainage with the root zone water quality model and a new model WAFLOWM. Trans. ASAE 38, 75–83.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: a Simulation Model of Maize Growth and Development. Texas A & M Press, College Station, Tx p. 194.

Klute, A., 1986. Water retention: laboratory method. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, second ed Agronomy Monograph 9. ASA and SSSA, Madison, WI, USA.

Kumar, A., Kanwar, R., Singh, P., Ahuja, L., 1999. Evaluation of the root zone water quality model for predicting water and NO_3–N movement in Iowa soil. Soil Till. Res. 50, 223–236.

Legates, D., McCabe, G., 1999. Evaluating the use of goodness of fit measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35 (1), 133–241.

Leslie, P.H., 1945. On the use of matrices in certain population mathematics. Biometrika 33, 183–212.

Loague, K., Green, R., 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Cont. Hydrol. 7, 51–73.

Ma, L., Shaffer, M., Boyd, B., Waskom, R., Ahuja, L., Rojas, K., Xu, C., 1998. Manure management in an irrigated silage corn field: experiment and modeling. Soil Sci. Soc. Am. J. 62, 1006–1017.

Ma, L., Ahuja, L., Ascough II., J., Shaffer, M., Rojas, K., Malone, R., Cameira, M.R., 2000. Integrating system modeling with field research in agriculture: applications of the root zone water quality model (RZWQM). Adv. Agron. 71, 233–293.

Monteith, J.L., 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19, 205–234.

Nimah, M., Hanks, R., 1973. Model for estimating soil–water–plant–atmospheric interrelation: I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37, 522–527.

Nokes, S., Landa, F., Hanson, J., 1996. Evaluation of the crop component of the root zone water quality model for corn in Ohio. Trans. ASAE 39, 1177–1184.

Ritchie, J.T., Burnett, E., 1971. Dry land evaporative flux in a sub-humid climate: II. Plant influences. Agron. J. 63 (1), 56–62.

Shuttleworth, W.J., Gurney, R., 1990. The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q. J. R. Meterol. Soc. 116, 497–519.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops—an energy combination approach. Q. J. R. Meterol. Soc. 111, 839–855.

Singh, P., Kanwar, R., Johnsen, K., Ahuja, L., 1996. Calibration and evaluation of subsurface drainage component of RZWQM V. 2.5. J. Environ. Qual. 25, 56–63.

Timlin, D.J., Ahuja, L., Ankeny, M., 1994. Comparison of three field methods to characterize apparent macropore conductivity. Soil Sci. Soc. Am. J. 58, 278–284.

Wright, J.L., 1981. Crop coefficients for estimates of daily crop evapotranspiration. In: Irrigation Scheduling for Water and Energy Conservation in the 80's (Proceedings of the Irrigation Scheduling Conference, Dec 1981), ASCE, pp. 18–26.